Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Theoretical Limitations on Shielding and Reflective Properties of Microwave Metamaterial Absorbers

Aleksey Solovey
L-3 Technologies ESSCO, Ayer, MA, USA
Aleksey.Solovey@L3T.com

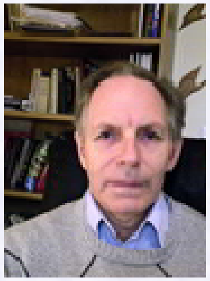
Copyright

Abstract

Theoretical limitations on shielding and reflective properties of a thin layer of passive microwave magneto-dielectric metamaterial absorbers that follow solely from the boundary conditions were numerically investigated. It was found that the boundary conditions do not limit the properties of the metamaterial absorbers and the perfect, as thin as required absorber layer whose absorption level is higher than specified above certain cut-off frequency can be made by means of the magneto-dielectric metamaterial. For that, all metamaterial features such as permittivity and permeability polarization and incident angle dependence, as well as lesser than one, or even negative values of real parts of permittivity and permeability must be employed. For only magnetic or only dielectric metamaterial absorbers while the transmission, reflection and total absorption levels still do not depend on the absorber thickness. However, its absorption properties start to degrade above 30º – 40º incidence due to the raise of the absorber reflectivity and then, above 75º of incidence due to the increase of transmission through the absorber approaching to 50% of total absorption at 90º incidence (evenly broken between the transmission through and reflection from the absorber).

Keywords: *Perfect absorbers, Metamaterials, Boundary conditions.*

Biography



Aleksey Solovey received degree in electro-physics from Novosibirsk State Technical University, Novosibirsk, Russia at 1972, and the Ph.D. degrees in radio-physics from Tomsk State University, Tomsk, Russia at 1994. From 1972 to 1994, he was Teaching and Research Assistant/Lecturer with Novosibirsk State Technical University. From 1996 to 1998, he was an Electronics Engineer with the Air Force Research Lab at Hanscom AFB, Bedford, MA, USA. From 1999 to 2007 he was lecturer at Wentworth Institute of Technology, Boston, MA, USA. At 2001 he joined L3 Technologies, ESSCO, Ayer, MA, USA where he currently serves as a Senior Principal, Electromagnetics. His research interests are concentrated around of various aspects of computational electromagnetics and its application to the antenna and radome design. He has (co)authored the book chapter and over 40 journals papers and conference presentations. He serves as a reviewer for two antenna and microwave journals and is a member of IEEE since 1996.

I. INTRODUCTION

Growing number of commercial and military applications that require microwave absorbers whose thickness is tiny fraction of the wavelength in vacuum stimulates the development of novel microwave absorbing metamaterials [1]. Conditions for complex permittivity and permeability which yield the lowest reflectivity along with highest shielding effectiveness were studied in [2] for conventional absorber materials. The current paper presents the results of similar numerical study for metamaterial absorbers.

Unlike conventional microwave absorber materials with real parts of relative permittivity and permeability close to or greater than 1 and weak frequency, polarization and incident angle dependences, the metamaterials might have significantly less than 1 or even negative real part of relative permittivity and permeability [3] with strong dependence on frequency, polarization and angle of incidence [4]. This gives metamaterial absorbers an edge over conventional absorbers.

As a rule, even very thin metamaterial absorbers have complicated, multilayer structure. However, as long as its thickness is significantly less than the wavelength, they can be represented by an equivalent single layer [6] with certain effective permittivity and/or permeability, which is beneficial from the analysis and design optimization standpoints [7]. Moreover, unlike thick absorbers described in [9], its absorption does not rely on the resonance within the absorber layer(s) and thus, is more broadband. For these reasons, thin layer of metamaterial absorber was studied based on the well-known expressions for reflection and transmission coefficients for the half-space plane material boundary [5] or the infinite plane sheet of a magneto-dielectric [8].

II. ABSORPTION OF THIN METAMATERIAL ABSORBER

Let's consider a plane wave that propagates from the half-space 1 (air/vacuum) to the half-space 2 (absorber) at the incidence angle θ. The relative refractive index n and wave impedance z are determined by the relative complex permittivity ε and permeability μ of the absorber material [5]:

$$n = \sqrt{\mu\varepsilon} \qquad z = \sqrt{\mu/\varepsilon} \tag{1}$$

Application of boundary conditions [5] leads to the following expressions for the TE and TM reflection coefficients and the normal to boundary surface component of the complex wave propagation vector within the absorber:

$$k_{2n} = k_1\sqrt{n^2 - sin^2\theta} = k_1(\beta - j\alpha)$$

$$R_{TE} = \frac{z\,cos\theta - \sqrt{n^2 - sin^2\theta}}{z\,cos\theta + \sqrt{n^2 - sin^2\theta}}$$

$$R_{TM} = \frac{cos\theta - z\sqrt{n^2 - sin^2\theta}}{cos\theta + z\sqrt{n^2 - sin^2\theta}} \tag{2}$$

where, k_1 is the wave number in air/vacuum, k_{2n} is the normal to boundary component of complex wave propagation vector within the absorber, $\beta \geq 0$ is relative propagation constant along the direction perpendicular to the boundary, and $\alpha \geq 0$ is the relative attenuation constant that should satisfy the following condition:

$$\alpha\, t/\lambda \geq A\;/\;54.575 \tag{3}$$

where, A is the required absorber attenuation expressed in dB, t is the thickness of the absorber layer and λ is the wavelength in vacuum. As it follows from (3), for high quality thin absorbers α should be much greater than 1.

A) Thin Magneto-Dielectric Metamaterial Absorbers

In spite of two independently varying complex parameters ε and μ it's impossible for conventional magneto-dielectric to satisfy the inequality (3) with reflection coefficients R_{TE} and R_{TM} in (2) simultaneously equal to zero using any combination of n and z, and/or ε and μ incident angle independent material parameters. As it follows from (1) – (3) to make R_{TE} equals to zero at given value of α defined by (3), values of and ε and μ material parameters must be equal to:

$$\varepsilon_{TE} = \frac{n\,cos\theta}{\sqrt{n^2 - sin^2\theta}} \qquad \mu_{TE} = \frac{n\sqrt{n^2 - sin^2\theta}}{cos\theta} \tag{4}$$

where, the refractive index n defined through (2) and (3) by absorption requirements. As it also follows from (1) – (3), to make R_{TM} equals to zero at the same given value of α and β, values of ε and μ in (4) just have to reverse its place i.e.,

$$\varepsilon_{TM} = \mu_{TE} \qquad \mu_{TM} = \varepsilon_{TE} \tag{5}$$

Expressions (2) – (5) indicate that perfect and as thin as required absorber layer whose absorption is higher than specified above the cut-off frequency defined by (3) can be made by means of the magneto-dielectric metamaterial. For that, all metamaterial features such as permittivity and permeability polarization and incident angle dependence, as well as lesser than one, or even negative values of real parts of permittivity and permeability must be employed.

As is seen from (2) – (5) for thin absorbers with $\alpha >> 1$, the real parts of the ε_{TE} and μ_{TM} are close to cosine of incidence angle having small positive imaginary part at the oblique incidence. The real parts of the ε_{TM} and μ_{TE} have quadratic dependence on α and β being negative when $\alpha > \beta$, while its imaginary parts are negative and proportional to the product of α and β. The real and imaginary parts of ε_{TM} and μ_{TE} are the reciprocal function of cosine of incidence angle.

Expressions (2) – (5) provide wide range combinations of ε and μ material parameters as function of two non-negative values β and α that constitute perfect magneto-dielectric metamaterial absorber. The lowest value of α is defined by (3), while the non-negative value of β is completely unrestricted. Thus, it's worth to investigate the sensitivity of absorption and reflection levels with respect to the absorber material parameter tolerances at different values of β and α.

First, it's sufficient to consider only the TE wave incidence and then apply the results to the TM wave case based on (5). Second, based on (3), it's always possible to select the parameter α big enough to achieve the required level of absorption within the absorber layer for any tolerance associated with ε_{TE} and μ_{TM} material parameters. Thus, the only tolerance sensitivity of the TE reflection coefficient has to be investigated.

As it follows from (2) and (4) the reflection coefficient R_{TE} does not depend on μ_{TE} at normal incidence and asymptotically, at large values of μ_{TE}, at the oblique incidence. Hence, for thin, high quality absorbers even significant deviation from optimal values of μ_{TE} does not meaningfully increase the reflection coefficient. This is illustrated on Figs. 1 and 2 where the power reflection coefficient is shown as function of β/α at various incident angles. Plots on Figs. 1 and 2 can be used for a reference, since the power reflection coefficient behaves as $1/\alpha^4$ and roughly as a square of a relative error δ of real and imaginary part of μ_{TE}. More precisely, it varies as $\delta^{2.5}$ and $\delta^{1.6}$ for the negative and positive deviation of real part, and as $\delta^{2.2}$ and $\delta^{1.8}$ for the negative and positive deviation of imaginary part of μ_{TE}, respectively.

Similar dependences for the ε_{TE} are shown in Figs. 3 and 4 that can also be used for a reference. For ε_{TE} deviations the power reflection coefficient behaves as $1/\alpha^4$ for the imaginary part and practically does not depends on α for the real part of ε_{TE}, still depending roughly as a square of a relative error δ of real and imaginary parts of ε_{TE}. More precisely, it varies as $\delta^{2.2}$ and $\delta^{1.8}$ for negative and positive deviation of real part and as δ^2 for negative and positive deviation of imaginary part of ε_{TE}, respectively.

Thus, for the magneto-dielectric absorbers whose parameter α satisfies (3) to ensure an acceptable level of absorption, no combination of non-negative values of α and β is preferable and the only somewhat tolerance sensitive material parameters are the real parts of the ε_{TE} and μ_{TM}.

Solid Red – Normal Incidence **Long-Dashed Dark Blue – 30° Inc.** **Short-Dashed Green – 50° Inc.**
Dot-Dashed Light Blue – 65° Inc. **Double Dot Yellow – 75° Inc.** **Triple Dot Purple – 90° Inc.**

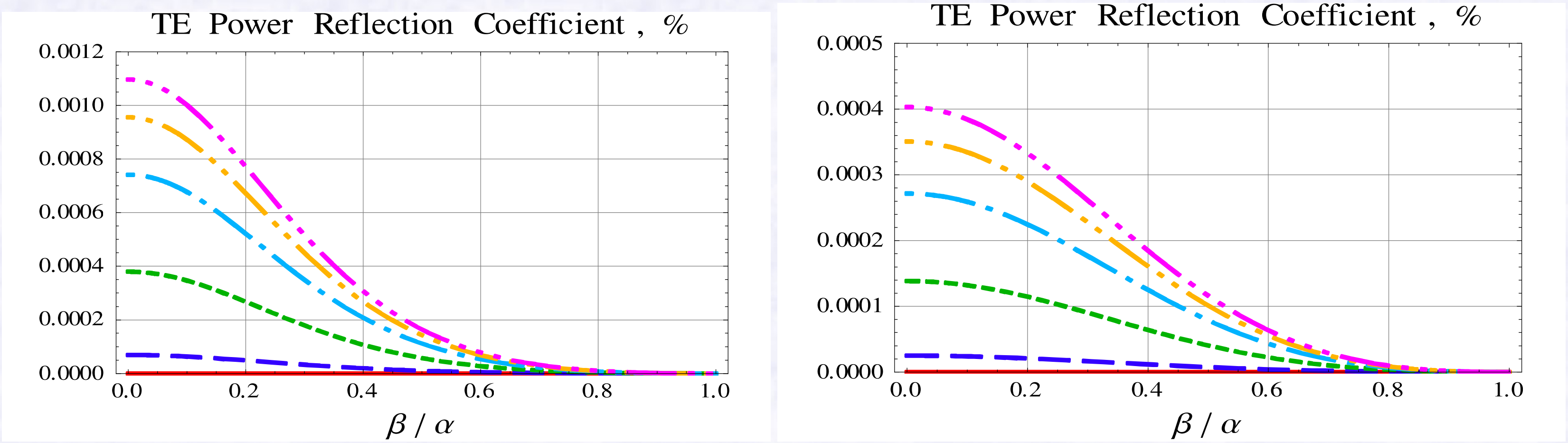


Fig.1 Power Reflection Coefficient when Relative Error of Real Part of μ_{TE} and ε_{TM} is -25% (left plot) or +25% (right plot) at $\alpha = 5$

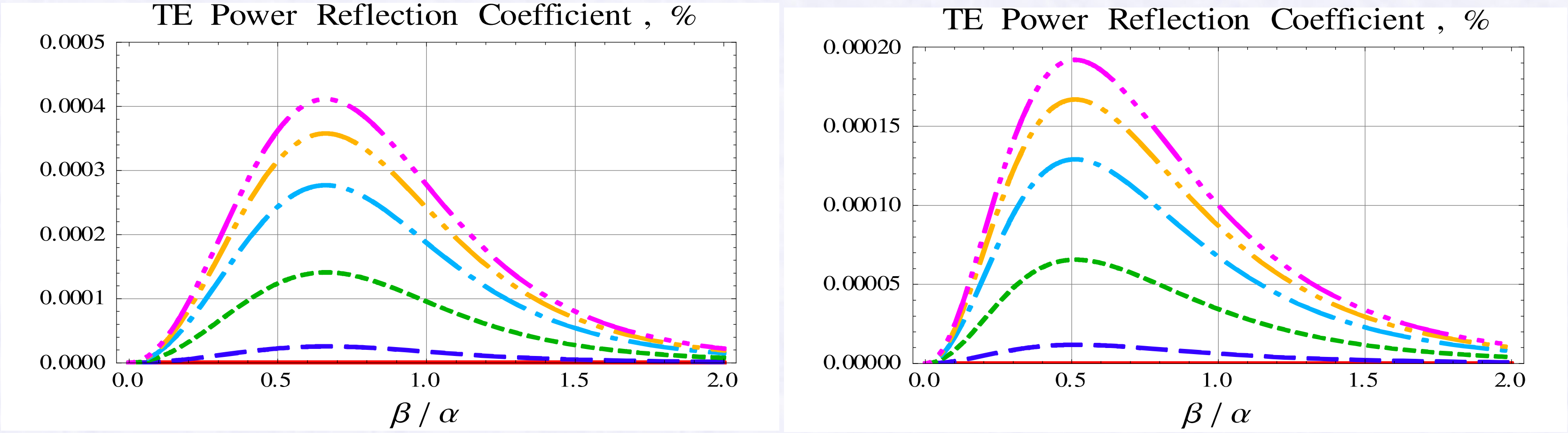


Fig.2 Power Reflection Coefficient when Relative Error of Imaginary Part of μ_{TE} and ε_{TM} is -25% (left plot) or +25% (right plot) at $\alpha = 5$

Solid Red – Normal Incidence **Long-Dashed Dark Blue – 30° Inc.** **Short-Dashed Green – 50° Inc.**
Dot-Dashed Light Blue – 65° Inc. **Double Dot Yellow – 75° Inc.** **Triple Dot Purple – 90° Inc.**

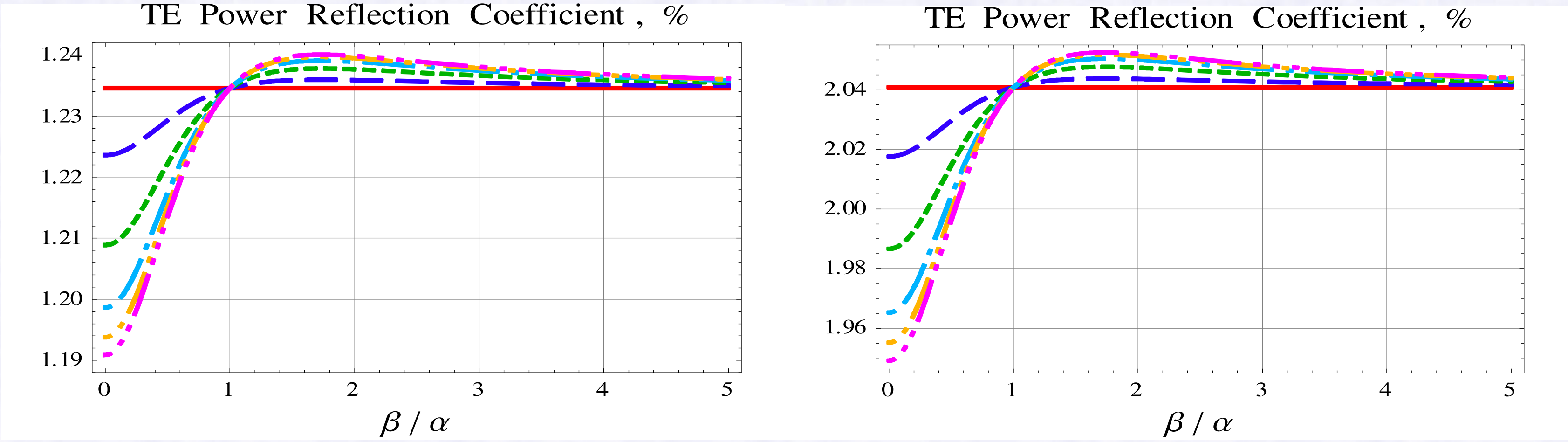


Fig.3 Power Reflection Coefficient when Relative Error of Real Part of ε_{TE} and μ_{TM} is -25% (left plot) or +25% (right plot) at $\alpha = 5$.

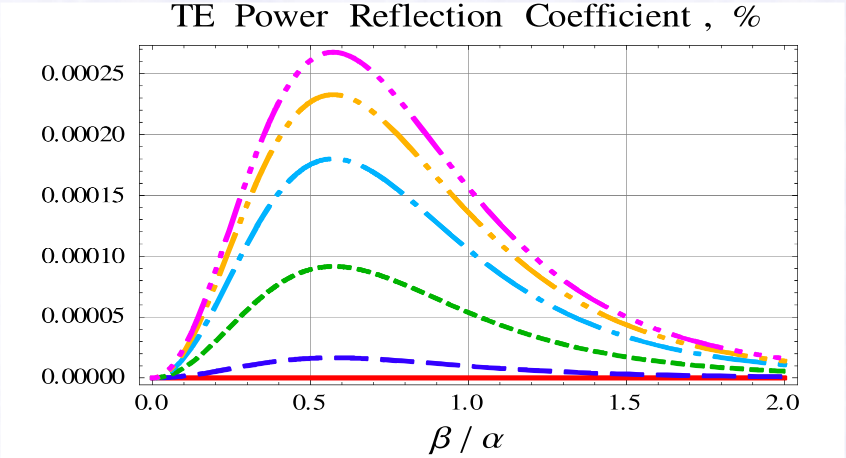


Fig.4 Power Reflection Coefficient when Relative Error of Imaginary Part of ε_{TE} and μ_{TM} is +25% or -25% at $\alpha = 5$.

B) Thin Magnetic or Dielectric Only Metamaterial Absorbers

Here the metamaterial absorbers that are only magnetic for TE and, based on (5), only dielectric for TM along with only dielectric for TE and only magnetic for TM incidences are investigated. Such metamaterial absorbers have less potentials than the magneto-dielectric ones due to its inability to achieve the desirable values of the parameters n and z that deliver zero reflection while keeping the near perfect absorption by varying just one, either μ or ε absorber material parameter. Thus, in this case, one cannot relying on (3) neglect the transmission through the absorber but instead, must maximize the total absorption using, for example, expressions for reflection R and transmission T of infinite flat layer of the magneto-dielectric given in [8]:

$$F = \exp(-jk_{2n}t) \qquad R = r(1-F^2)/(1-r^2F^2) \qquad T = F(1-r^2)/(1-r^2F^2) \tag{6}$$

where, r is either R_{TE} or R_{TM} reflection coefficient from (2).

The minimum of unabsorbed power obtained based on (2) and (6) for the thin layer of the TE magnetic or TM dielectric metamaterials with $\mu_{TM} = \varepsilon_{TE} = 1$ is shown in Fig. 5 for thin absorbers ($t/\lambda < 0.2$). It's remarkable that for thin absorbers the transmission, reflection and total absorption levels do not depend on the absorber thickness, although values of μ_{TE} and ε_{TM} that deliver this optimum absorption do depend on it. As is seen from Fig. 5 the TE magnetic (or the TM dielectric) metamaterial absorber starts to lose its absorption properties above 30º – 40º incidence due to the raise of the absorber reflectivity and then, above 75º of incidence due to the increase of transmission through the absorber.

Example of μ_{TE} or ε_{TM} values that correspond with the optimum absorption are shown in Fig. 6 for the case of $t/\lambda = 0.02$, where imaginary part of μ_{TE} or ε_{TM} below 80º – 85º incidence (depending on t/λ) can be arbitrary close to zero staying, however, on the negative territory. Values of optimum μ_{TE} and ε_{TM} are not tolerance sensitive and can vary from orders of magnitude near the normal incidence to several percentage points near 90º incidence not having meaningful variations of the absorption level. Optimum values of μ_{TE} or ε_{TM} increase with the decrease of the absorber thickness, which makes those absorbers frequency dependent at the oblique incidence.

Similarly to the TE magnetic (or the TM dielectric) case, the achievable minimum of unabsorbed power for the thin layer of the TE dielectric (or the TM magnetic) metamaterial does not depend on the absorber thickness. However, unlike to the previous case, it equals 50% (that evenly broken between the transmission through and reflection from the absorber regardless on the angle of incidence). That makes this kind of absorber materials impractical.

Solid Red – Total Unabsorbed Power **Long-Dashed Dark Blue – Reflected Power** **Short-Dashed Green – Transmitted Power**

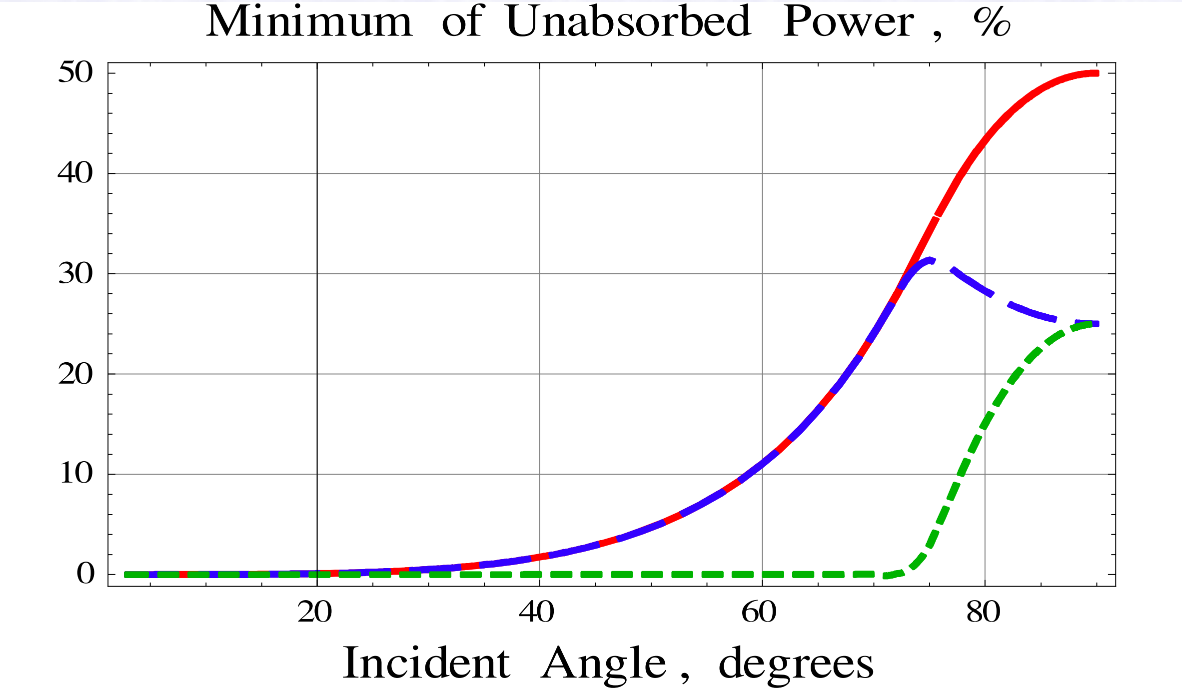


Fig.5 Total Minimum of Unabsorbed Power for $\mu_{TM} = \varepsilon_{TE} = 1$

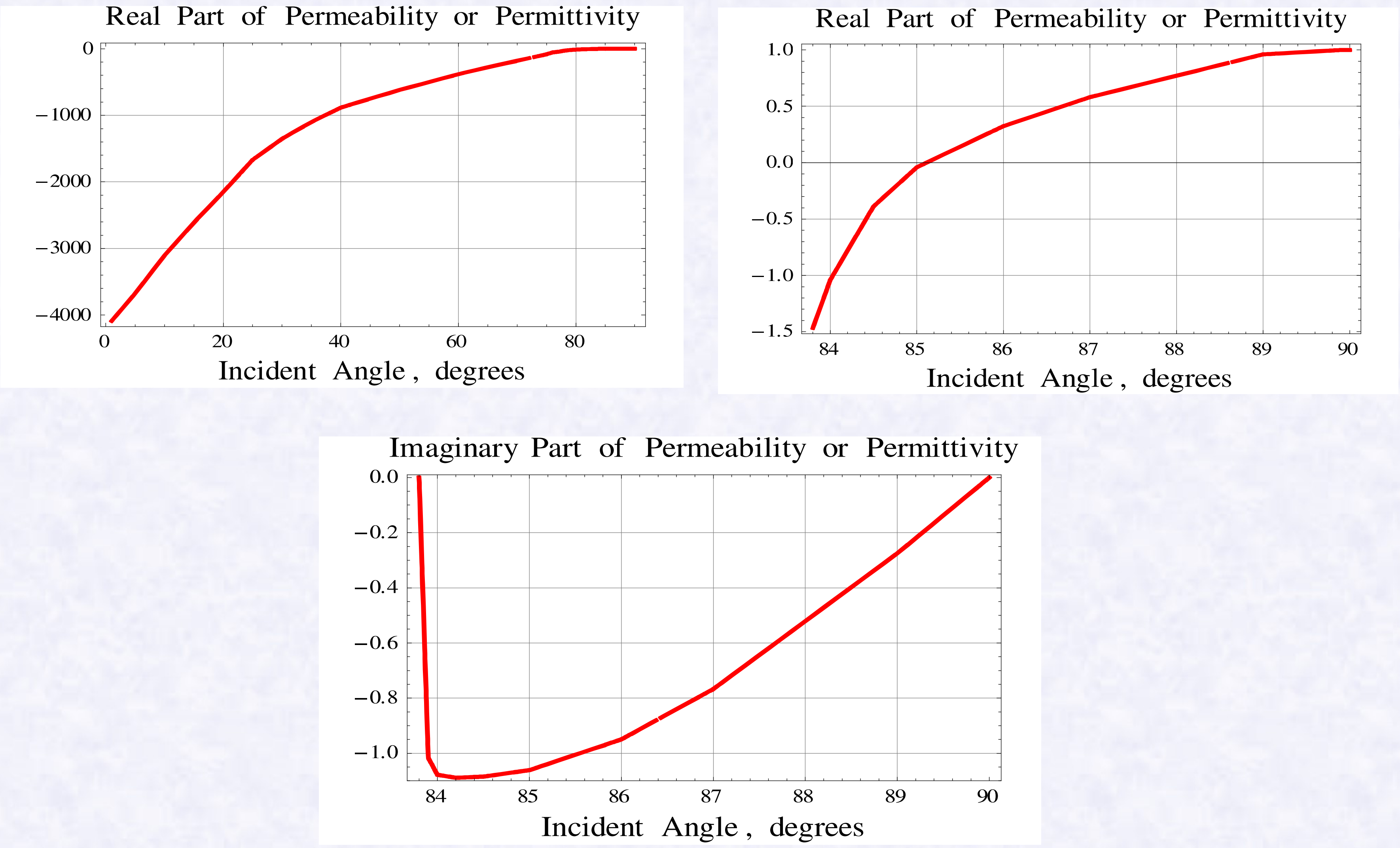


Fig.6 Optimum Values of Real and Imaginary Parts of Permeability for TE and Permittivity for TM Incidence at $\mu_{TM} = \varepsilon_{TE} = 1$ and $t/\lambda = 0.02$.

CONCLUSIONS

Perfect and as thin as required absorber with guaranteed absorption level above specified cut-off frequency defined by (3) can be made using the magneto-dielectric metamaterials. For that all specifically metamaterial attributes such as permittivity and permeability polarization and incident angle dependence as well as lesser than one, or even negative values of real parts of permittivity and permeability are essential.

There are infinite number of combinations of complex values μ and ε generated by two arbitrary non-negative parameters α and β that deliver any desirable absorption at zero reflection level for the arbitrary thin flat layer of magneto-dielectric metamaterial absorber.

For magneto-dielectric metamaterial absorbers the levels of reflection and absorption are not at all tolerance sensitive, with the exception of very modest tolerance sensitivity for the real parts of ε_{TE} and μ_{TM}.

For thin metamaterial absorbers ($t/\lambda < 0.2$) with only TE magnetic ($\varepsilon_{TE} = 1$) or only TM dielectric ($\mu_{TM} = 1$) material parameters the achievable minimum of unabsorbed power does not depend on the absorber thickness while depending on angle of incidence.

For only TE magnetic and only TM dielectric metamaterial absorbers optimal values of μ_{TE} and ε_{TM} sharply vary with the thickness of metamaterial layer and the incidence angle. Values of optimum μ_{TE} and ε_{TM} are not tolerance sensitive, being although frequency dependent.

For thin metamaterial absorbers with only TM magnetic ($\varepsilon_{TM} = 1$) and only TE dielectric ($\mu_{TE} = 1$) material parameters the total unabsorbed level equals to 50% at all incidence angles being broken evenly between the transmission through and reflection from the absorber. That makes this kind of absorber materials impractical.

REFERENCES

[1] H. Li, L. H. Juan, B. Zhou, X. P. Shen, Q. Cheng, and T. J. Cui. “Ultrathin Multiband Gigahertz Metamaterial Absorbers”, J. Appl. Phys., Vol. 110, pp. 0149091 – 0149098, 2011.

[2] Aleksey Solovey, Raj Mittra. “Theoretical Limitations on Shielding and Reflective Properties of Microwave Absorbers”, Proceedings the 39th European Microwave Conference. pp. 1614-1617, Rome, Italy September 28 – October 2, 2009.

[3] Veselago V. G., “The Electrodynamics of Substances with Simultaneously Negative Values of ε and μ”, Soviet Physics Uspekhy, Vol. 10, No. 4, pp. 509-514, 1968.

[4] X. Shen, T. J. Cui, J. Zhao, H. F. Ma, W. X. Jiang, and H. Li. “Polarization-independent Wide-angle Triple-band Metamaterial Absorber”, Optic Express, Vol. 19, pp. 9401-9407, 2011.

[5] V. I. Volman and Yu. V. Pimenov, Technical Electrodynamics, 2nd ed., Moscow, Russia: Svyaz, 1971.

[6] A. D’Aloia, M. D’Amore, and M. Sabrina. “Terahertz Shielding Effectiveness of Graphene-Based Multilayer Screen Controlled by Electric Field Bias in Reverberating Environment”, IEEE Trans. on Terahertz Sci. and Tech., Vol.5. No 4, July 2015.

[7] P. Zhou, L. Huang, D. Liang, H. Lu and L. Deng. “Prediction of Microwave Absorption Behavior of Grading Honeycomb Composite Based on Effective Permittivity Formulas”, IEEE Trans, on AP, Vol. 63, No. 8, pp. 3496-3501, Aug. 2015.

[8] L. N. Ridenour, Editor-in-Chief, “Radar Scanners and Radomes”, Part II, pp. 355–356, MIT Radiation Laboratory Series. McGraw-Hill, 1948.

[9] J. Chen, Z. Hu, G. Wang, X. Hyang, S. Wang and M. Liu. “High-Impedance Surface-Based Broadband Absorber with Interference Theory”, IEEE Trans, on AP, Vol. 63, No. 10, pp. 4367-4374, Oct. 2015.